Evolution of the Inner Circumstellar Envelope of V838 Monocerotis

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ABSTRACT

We present imaging polarimetry observations of the eruptive variable V838 Monocerotis and its neighboring field obtained in 2002 October. The polarization of field stars confirms the previously determined interstellar polarization along the line of sight to V838 Mon. While V838 Mon showed intrinsic polarization shortly after its second outburst on 2002 February 8, all subsequent observations only showed a quiescent interstellar polarization component. We find V838 Mon once again showed significant intrinsic polarization in 2002 October, suggesting the presence of an asymmetrical geometry of scattering material close to the star. Furthermore, an observed 90° position angle flip in the intrinsic polarization from 2002 February to 2002 October suggests that the distribution of nearby circumstellar material has experienced significant changes. We discuss the opacity changes in the evolving circumstellar cloud around V838 Mon that may explain these observations.

Subject headings: circumstellar matter — stars: individual (V838-Mon) — techniques: polarimetry

1. Introduction

The eruptive variable V838 Monocerotis, first reported as a possible nova on 2002 January 6.6 (Brown et al. 2002), experienced three significant photometric outbursts in early 2002 (Munari et al. 2002a; Kimeswenger et al. 2002). From pre-outburst to its maximum brightness during the second outburst, V838 Mon brightened by over nine magnitudes in V, from 15.85 to 6.66 (Goranskii et al. 2002). V838 Mon also exhibited significant spectroscopic variability in early 2002: neutral metal and s-process lines were observed following

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the first outburst (Zwitter & Munari 2002), ionized metal lines were noted following the second outburst (Iijima & Della Valle 2002; Morrison et al. 2002), and neutral metal and molecular lines were observed following the third outburst (Rauch et al. 2002; Banerjee & Ashok 2002). V838 Mon exhibited intrinsic polarization on 2002 February 8 (Wisniewski et al. 2003). Polarimetric observations after 2002 February 13 only detected the presence of an interstellar polarization (ISP) component (Munari et al. 2002b; Wisniewski et al. 2003).

V838 Mon developed a light echo by 2002 February 17 (Henden et al. 2002). Bond et al. (2003) obtained imaging polarimetry of this light echo with HST ACS, and suggested a distance of 3 to 7 kpc to V838 Mon, although a wide range of other distances have been estimated (e.g. see discussion in Wisniewski et al. 2003 and Tylenda 2003). In late September and early October of 2002, V838 Mon's spectral type had evolved to "later than M10-III" (Desidera & Munari 2002). Furthermore, a weak blue continuum was detected by several groups, suggesting that a binary component of spectral type B3V might be present (Desidera & Munari 2002; Wagner & Starrfield 2002; Munari et al. 2002c). Recent MMT spectra confirm this secondary component (Starrfield, private communication).

Given the magnitude and complexity of the variability exhibited by V838 Mon, it is not surprising that there is still great uncertainty regarding the exact nature of this object. In this paper, we present imaging polarimetry observations of V838 Mon and its surrounding field obtained in 2002 October. These observations allow us to further interpret the evolution of the circumstellar matter near V838 Mon since its major outbursts.

2.   Observations

We obtained polarimetric measurements of V838 Mon and its field in 2002 October at the CTIO 1.5 m telescope. The standard Cassegrain focus imaging camera with the f/13.5 (0.24 arcsec pixel^{-1}) configuration was modified by the addition of a rotatable half-wave plate followed by a fixed analyzer placed before the second filter wheel. The analyzer was a double calcite block whose optical axes had been crossed to minimize astigmatism and color effects, which produced two orthogonally polarized images of each object in the field. One polarization modulation is covered for each 90° rotation of the waveplate. For our V, R, and I observations of V838 Mon, we took images with the waveplate rotated through 8 positions 22.5° apart. Further details about this polarimeter can be found in Magalhães et al. (1996), Melgarejo et al. (2001), & Pereyra & Magalhães (2002).

After basic image processing in IRAF[3], we performed aperture photometry on the fields. The reduction package PCCDPACK (Pereyra 2000), which calculates linear polarization from a least squares solution of the photometry in the 8 waveplate positions (ψ_i), was then applied. The residuals at each waveplate position with respect to the expected $\cos 4\psi_i$ curve constitute the uncertainties in our data; these are consistent with the theoretically expected photon noise errors (Magalhães, Benedetti, & Roland 1984). Each object whose polarization is reported has been carefully checked for contamination effects due to close neighbors; objects which contained such contamination were excluded from the present study.

Polarized and unpolarized standard stars were monitored nightly throughout the eleven nights of our observing run, and the stability of the polarimeter was reflected in the consistency of these standard star observations. Comparing our observations of polarized standard stars to available literature data, we transformed our polarization measurements to a standard equatorial system. This transformation is accurate to a position angle (PA) of better than 1°. Instrumental polarization was consistently less than 0.05%. Note that the simultaneous observation of the dual orthogonally polarized images of each target in each waveplate position allows for accurate polarimetry to be performed even under non-photometric skies, as all sky polarization is practically canceled (Magalhães et al. 1996). We summarize our observations of V838 Mon, along with polarimetry of this object from the literature, in columns 1-5 of Table 1.

3.   Results

3.1.   Polarization of Field Stars

Over small spatial regions, where variations in the distribution of dust and magnetic fields can be assumed to be small, field stars located at similar distances exhibit similar levels of interstellar polarization (ISP). To study the intrinsic polarization of an astrophysical object, it is often beneficial to examine the polarization of spatially nearby field stars, located at similar distances, to get a statistical measure of the ISP along a particular line of sight.

We measured the polarization in V, R, and I of most of the field stars surrounding V838 Monocerotis; a sample of these results is given in Table 2 and a complete listing of these data is available online. Figure 1a shows a V band image obtained on 2002 October 16 at the CTIO 0.9m, and includes numerical references to stars shown in Figure 1b and

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[3]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

tabulated in Table 2. A plot of the spatial distribution of the polarization of these field stars in the V band is shown in Figure 1b. We note that three stars near V838 Mon show very similar polarizations to each other, star #2, star #3, and star #5. Furthermore, these stars exhibit very similar polarizations to the ISP previously estimated for V838 Mon (Wisniewski et al. 2003). We plot the wavelength dependence of the polarization of these three objects in Figure 2, and overlay the modified Serkowski law (Serkowski et al. 1975; Wilking et al. 1982) description of V838 Mon's interstellar polarization with $P_{max} = 2.746 \pm 0.011\%$, $\lambda_{max} = 5790 \pm 37 \overset{\circ}{A}$, $PA = 153.43 \pm 0.12°$, $\delta PA(\lambda) = 0$, and $K = 0.971$ (Wisniewski et al. 2003). The good agreement shown in this figure supports the previously determined ISP, derived entirely from spectropolarimetry. Furthermore, these results imply that stars #2, #3, and #5 are located at similar distances as V838 Mon. Future efforts to determine the distance to V838 Mon should ensure consistency with these three neighboring objects.

3.2. Intrinsic Polarization of V838 Mon

We subtracted the ISP along the line of sight (Wisniewski et al. 2003) from our observations of V838 Mon to determine its intrinsic polarization. The non-zero results (columns 6-8, Table 1) show that on 2002 Oct 22-24 V838 Mon once again exhibited a significant intrinsic polarization component. Interestingly, the magnitude of intrinsic polarization present on 2002 October 22-24 is similar to that observed on 2002 February 8; however, the position angle of this scattered light differs by roughly 90°, e.g. a PA "flip" has occurred.

The presence of an intrinsic polarization component can be interpreted as a signature of light scattering off circumstellar material which is distributed in an asymmetrical geometry. The intrinsic polarization reported here and by Wisniewski et al. (2003) is produced in a region immediately surrounding the unresolved central star, and as such is different from the reported polarization of V838 Mon's light echo (Bond et al. 2003). In our observations of the unresolved source, the observed polarization is roughly the ratio of the scattered to total (i.e. direct plus scattered) light received. Thus the renewed intrinsic polarization component suggests that either a) a new source of asymmetrical circumstellar material, i.e. a new source of scatterers, formed around V838 Mon in 2002 October; b) the opacity of the circumstellar envelope surrounding V838 Mon evolved significantly between February 5 to February 13 to October 22-24, thereby changing the dominant source of scattered light over time; c) the illuminating source had changed; or d) a combination of the aforementioned scenarios.

4. Discussion

Schulte-Ladbeck et al. (1992) interpreted an observed wavelength-dependent PA flip in polarimetric observations of an unresolved B[e] star as evidence of a bipolar nebula. These authors argued that at short wavelengths an optically thick circumstellar disk blocked out most starlight and thus little scattered light (with a PA aligned along the polar axis) originated from the equatorial disk. Most of the polarized light at short wavelengths originated from the polar regions, where the resulting PA would be aligned with the equatorial disk. At long wavelengths, where the disk was optically thin, the dominant source of scattered light was the equatorial disk region, not the polar regions. The net effect of such a wavelength dependent opacity effect was the production of a 90° PA flip in the polarization signal at the wavelength where the equatorial and polar regions contributed equal amounts of scattered light.

We suggest that a similar type of scenario might explain the renewed intrinsic polarization component and PA flip in V838 Mon. On 2002 February 8, V838 Mon had an intrinsic polarization component, indicating the presence of an asymmetrical distribution of circumstellar material, initially suggested to be a flattened circumstellar envelope (Wisniewski et al. 2003). We postulate that at this initial stage, the observed scattered light originated primarily from specific physical locations, e.g. the polar region. As the opacity of the circumstellar material evolved over time, specifically as the opacity of the equatorial material decreased, we suggest that the contribution of scattered light from the polar and equatorial regions were nearly equivalent. Thus, viewed as an unresolved object, the scattered light from the circumstellar envelope would appear to be unpolarized, consistent with observations in late 2002 February and March (Wisniewski et al. 2003; Munari et al. 2002b). As the envelope continued to evolve and the equatorial region experienced a further decline in opacity, one would expect the equatorial region to slowly emerge as the dominant source of scattered light. This re-emergence of a dominant (and secondary) scattering region would produce an intrinsic polarization component oriented 90° from the original position angle. The projection of the intrinsic PA of this envelope onto the sky (2 $\theta \sim 75°$, measured N to E) is not inconsistent with the overall morphology seen in the HST ACS images (Bond et al. 2003). The intrinsic PA of the polar region is also not inconsistent with the direction of the hole in the HST ACS light echo images.

We note that the opposite relative opacity changes would produce a similar PA flip. The scattered light in the circumstellar envelope could have initially been dominated by an optically thin disk. As this equatorial material dispersed, the scattered light from the equatorial and polar regions could have balanced, producing zero intrinsic polarization. Over time, expansion of the disk could have evacuated the equatorial region, causing the polar

region to emerge as the dominant source of scattered light.

Followup infrared (IR) imaging polarimetry would be valuable in providing additional constraints on the nature of V838 Mon's circumstellar envelope. Based upon infrared (IR) light and color curves, Crause et al. (2003) suggest that a dust shell had formed around the central star by 2002 April. If in early 2002 this dust formed in the equatorial regions as described in the aforementioned first scenario, i.e. an initial thick equatorial and thin polar region, then the IR polarization position angle would be the same as that quoted in this paper.

As described in the introduction of this paper, V838 Mon appears to have a binary companion. Polarimetric observations of mass transfer binary systems show some degree of periodicity and scattering at a constant PA, defined by the orbital plane of the system (Hoffman et al. 1998). The observed PA flip in V838 Mon's intrinsic polarization, along with the lack of any apparent periodicity, suggest that binarity is not the dominant source of scatterers responsible for the observed intrinsic polarization component.

In summary, the polarization of field stars confirms the previously suggested interstellar polarization along the line of sight to V838 Mon. We find strong evidence of a renewed intrinsic polarization component in V838 Mon, at a position angle nearly 90° from that present on 2002 February 8. We suggest that these observations indicate an evolution of the circumstellar environment of V838 Mon, possibly characterized by: 1) an initially optically thick equatorial disk which contributed a limited amount of scattered light; 2) a subsequent decline in disk opacity resulted in a balance of scattered light produced by the polar and equatorial regions; and 3) the further decline in the opacity of the equatorial disk finally allowed the equatorial region to become the dominant source of scattered light. Continued spectropolarimetric monitoring of V838 Mon is strongly encouraged, as such observations would enable detailed modeling of the circumstellar environment of this unique object to be performed.

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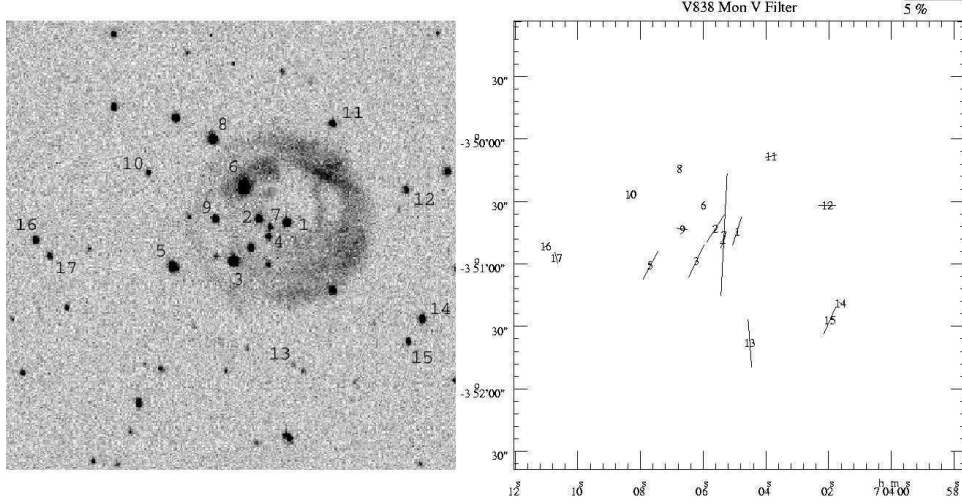Zwitter, T. & Munari, U. 2002 IAU Circ., 7812

Fig. 1.— Fig 1a: The location of the field stars cited in Figure 1b and in Table 2 are overlayed on a V band image of the field of V838 Mon, taken with the CTIO 0.9m. V838 Mon is labeled as number 1. Fig 1b: Polarization of V838 Mon and surrounding field stars.
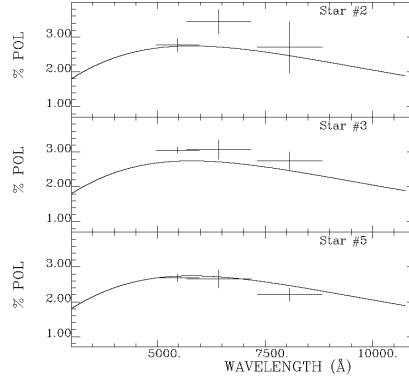

Fig. 2.— The wavelength dependence of three nearby field stars of V838 Mon is shown, along with an overlay of the interstellar polarization Serkowski fit derived by Wisniewski et al. (2003) from spectropolarimetry in early 2002. These field stars are consistent with this previously determined ISP.

Table 1:

Filter	Date	%P	%Err	PA	Intrinsic %P	%Err	Intrinsic PA	Remarks
B	2002 Feb 8	2.840	0.081	146.6	0.703	0.081	117.0	Wisniewski et al. (2003)
V	2002 Feb 8	3.412	0.012	146.7	0.983	0.012	127.0	Wisniewski et al. (2003)
V*	2002 Feb 13	2.729	0.009	153.4	$\cdots$	$\cdots$	$\cdots$	Wisniewski et al. (2003)
V	2002 Oct 24, 08:12UT	2.49	0.12	162.3	0.90	0.12	32.0	this study
V	2002 Nov 12	3.05	0.35	159.7 ± 3.9	$\cdots$	$\cdots$	$\cdots$	Giro et al. (2002)
5500Å	2002 Feb-March	2.6	$\cdots$	150 ± 2	$\cdots$	$\cdots$	$\cdots$	Munari et al. (2002b)
R	2002 Feb 8	3.226	0.004	149.0	0.714	0.004	131.2	Wisniewski et al. (2003)
R	2002 Feb 13	2.667	0.004	153.4	$\cdots$	$\cdots$	$\cdots$	Wisniewski et al. (2003)
R	2002 Oct 22, 08:57UT	2.24	0.21	163.2	0.93	0.21	36.7	this study
I	2002 Feb 8	2.910	0.003	149.5	0.578	0.003	131.9	Wisniewski et al. (2003)
I	2002 Feb 13	2.458	0.003	153.5	$\cdots$	$\cdots$	$\cdots$	Wisniewski et al. (2003)
I	2002 Oct 24, 08:46UT	2.23	0.04	156.3	0.32	0.04	42.1	this study

Note. — Summary of our observations of V838 Monocerotis, as well as literaure polarimetric observations. The * superscript denotes a spectropolarimetric observation which did not span the entire wavelength range of the Johnson V filter, thus the V band polarization for this observation is thus only an estimate. Wisniewski et al. (2003) suggested, and the present field star measurements support, that the polarization of V838 Mon on 2002 February 13 was purely interstellar in origin. We determined the intrinsic polarization present on 2002 October 22-24 by subtracting the observed polarization on 2002 February 13 from our data.

Table 2:

RA(2000)	Dec(2000)	Fig. 1 Ref.	Filter	%P	%Err	PA
7:04:05	-3:50:50	1	V	2.486	0.118	162.3
...	...	...	R	2.236	0.209	163.2
...	...	...	I	2.230	0.043	156.3

Note. — Filter polarimetry of targets shown in Figure 1a,b. The reference numbers in column three refer to the labels in Figure 1a,b. The complete version of this table is in the electronic edition of the Journal.